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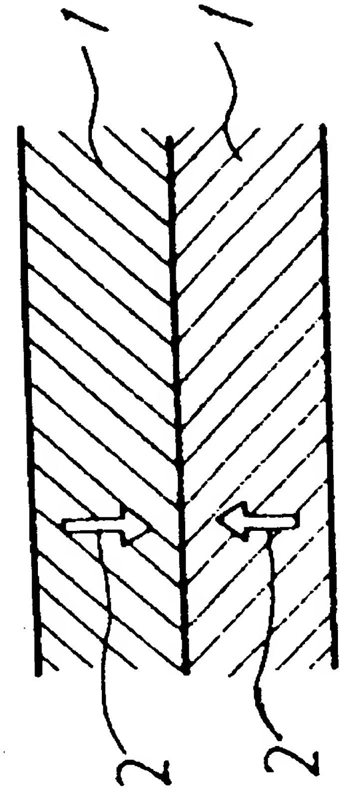

ABSTRACT : PURPOSE: To obtain both side bimorph structures by laminating graft polymers of different contents of inorganic ferrodielectric fine powder to form a composite molding material, applying a DC electric field to the material, thereby polarizing the material to apply piezoelectricity of reverse polarity to the respective layers.

CONSTITUTION: Inorganic ferrodielectric fine powder of titanium cobalt tungstate lead zirconate fine powder is suspended in dispersant which contains radially polymerizable vinyl monomer and polymer latex. A graft polymer composite is obtained by containing in this suspension ball mill, graft polymerizing, washing and drying. In this case, the first and second sheetlike composites in which the ratios of the cobalt titanium tungstate lead zirconate contained in the composite are differentiated to 97.8% and 30.6% by weight are superposed, oriented by a superposition roll kneading calender molding method, thereby obtaining a sheetlike composite piezoelectric material. After Ag electrodes are provided by a vacuum deposition on both side surfaces of the material, a DC electric field of 150kV/cm is piezoelectric bimorph.

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ELECTROSTRICTIVE POLYMER ARTIFICIAL MUSCLE ACTUATORS

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Abstract

Many new robotic and teleoperated applications require a high degree of mobility or dexterity that is difficult to achieve with current actuator technology. Natural muscle is an actuator that has many features, including high energy density, fast speed of response, and large stroke, that are desirable for such applications. The electrostriction of polymer dielectrics with compliant electrodes can be used in electrically controllable, muscle-like actuators. These electrostrictive polymer artificial muscle (EPAM) actuators can produce strains of up to 30% and pressures of up to 1.9 MPa. The measured specific energy achieved with polyurethane and silicone polymers exceeds that of electromagnetic, electrostatic, piezoelectric, and magnetostrictive actuators. A simple model using linear elastic theory can predict EPAM actuator performance from mechanical and electrical material properties and load conditions. A spherical joint for a highly articulated (snake-like) manipulator using EPAM actuator elements has been demonstrated. A rotary motor using EPAM actuator elements has been shown to produce a specific torque of 19 mNm/g and a specific power of 0.1 W/g. An improved EPAM motor could produce greater specific power and specific torque than could electric motors.

Introduction

Robots, manipulators and unmanned vehicles are increasingly proposed for use in field applications that require a high degree of mobility or dexterity. Such applications might require the ability to traverse difficult terrain or access and manipulate objects within heavily obstructed work spaces. These abilities place stringent requirements on actuator performance. Lightweight and compact actuators that offer sufficient force and stroke in a rapid and controllable manner are needed. For mobile applications where mission duration is an issue, it is also important that the actuators be energy efficient.

The biological world provides numerous examples of creatures that are physically capable of undertaking tasks similar to those proposed for robots and for teleoperated manipulators and vehicles. Indeed many robots and manipulators under development are based on designs inspired by nature. Insect-like legged robot platforms are used to traverse difficult terrain [Shastri 1997]. Highly-articulated snake-like manipulators can access confined areas [Hirose 1993]. Worm-like robots are used for pipe inspection and endoscopy [Aramaki et al. 1995]. The biological analogs to these examples all employ muscle as actuators. Muscle meets the stringent requirements of these difficult applications. Muscle is ubiquitous as an actuator throughout the higher orders of the animal kingdom. The performance of muscle is scale invariant, i.e., independent of size or mass. Thus, we find muscles with similar performance in applications as diverse as moving the legs of microscopic mites and lifting the trunk of an elephant. It follows that an actuator with muscle-like performance would be well suited to a wide variety of robots and unmanned vehicles.

Several researchers have noted the potential of "artificial muscle" actuators for robotic applications. DeRossi and Chiarelli [1994], Hunter and Lafontaine [1992], Pelrine, Eckerle, and Chiba [1992], and Kornbluh, Eckerle, and Andeen [1991] survey technologies used in artificial muscle actuators. These technologies include electromagnetics, mechano-chemical polymers, electrochemomechanical polymers (conducting polymers), piezoelectric and magneto-strictive materials, shape memory alloys and polymers, electrostatics, hydraulics and pneumatics, thermal expansion and thermal phase change, and fuel burning engines. All of these technologies are distinctly different from muscle in certain aspects of their performance and are therefore not well suited to certain applications that require muscle-like actuation.

Frequently, actuator requirements are defined in terms of stroke and force (or torque) requirements. However, the use of transmissions can trade off force, speed and stroke. For example, a small motor can be attached to a lead screw to produce a slow but high-force and high-stroke, linear actuator. Table 1 compares

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actuation technologies, independent of any transmission systems. The metrics used in this comparison are energy density (energy output per unit volume) or specific energy (energy output per unit mass). These metrics describe how large or heavy an actuator would be have to be, to perform a given amount of work. When the speed of response of an actuator is an issue, its power density or specific power are also useful metrics for purposes of comparison. Power density and specific power can easily be calculated by multiplying the energy density or specific energy by the frequency of actuation (or by dividing these values by the speed of response).

Electrostrictive polymers and, in particular, electrostrictive polymers with low moduli of elasticity and highly compliant electrodes are used in a relatively new class of actuators that offer overall performance similar in some respects to that of biological muscle. This class of actuators is termed *electrostrictive polymer artificial muscle* (EPAM). Table 1 shows the performance of these actuators compared to that of several other electric actuation technologies and biological muscle. Note that EPAM technology does not provide the best performance according to any one metric. However, EPAM performance closely matches or exceeds that of biological muscle; it therefore follows that electrostrictive polymer actuators might be well suited to many robot, manipulator, and unmanned vehicle applications that require performance similar to that of biological creatures.

In the next section we briefly describe the operation of EPAM actuators, then experimental measurements of the electrostriction of several different polymer materials. Next we describe the potential use of electrostrictive polymer actuators in robots, manipulators, and unmanned vehicles, using two specific examples; a spherical joint actuator for a thin snake-like manipulator and a general purpose rotary motor. Each of these examples exploits the unique muscle-like features of EPAM actuators.

Table 1. Comparison of Actuator Technologies

Actuator Type (specific example)	Max Strain (%)	Max Pressure (MPa)	Max Energy Density (J/cm^3)	Max Efficiency (%)	Specific Density	Relative Speed (full cycle)
Electrostrictive Polymer Artificial Muscle[1]						
Silicone	32	0.21	0.034	90	1	Fast
Polyurethane	11	1.9	0.10	80	1	Fast
Electrostatic Devices (Integrated Force Array[2])	50	0.03	0.0015	>90	1	Fast
Electromagnetic (Voice Coil[3])	50	0.10	0.025	>90	8	Fast
Piezoelectric						
Ceramic PZT[4]	0.2	110	0.10	>90	7.7	Fast
Polymer(PVDF[5])	0.1	4.8	0.0024	90	1.8	Fast
Shape Memory Alloy (TiNi[6])	>5	>200	>5	<10	6.5	Slow
Shape Memory Polymer (Polyurethane[7])	100	4	2	<10	1	Slow
Thermal (Expansion[8])	1	78	0.4	<10	2.7	Slow
Electrochemo-mechanical Conducting Polymer (Polyaniline[9])	10	450	23	<1%	~1	Slow
Mechano-chemical Polymer/Gels (poly-electrolyte[10])	>40	0.3	0.06	30	~1	Slow
Magnetostrictive (Terfenol-D, Etrema Products[11])	0.2	70	0.025	60	9	Fast
Natural Muscle (Human Skeletal[12])	>40	0.35	0.07	>35	1	Med

1. Source: Pelrine, Kornbluh, and Joseph [1998].
2. Source: MCNC web site: http://www.mcnc.org/HTML/ETD/EMAD/ifa/ifa.html
3. These values are based on an array of 0.01 m thick voice coils, 50% conductor, 50% permanent magnet, 1 T magnetic field, resistivity of 2 ohm-cm, and 40,000 W/m^2 power dissipation.
4. PZT B, at maximum electric field of 4 V/μm, using data from Moulson and Herbet [1990], p. 293.
5. PVDF, at maximum electric field of 30 V/μm. Source: AMP literature, AMP Inc. Valley Forge, Pennsylvania, USA
6. Source: Hunter et al. [1991].
7. Source: Tobushi, Hayashi, and Kojima [1992].
8. Aluminum, using a temperature change of 500°C.
9. Source: Baughman et al. [1990].
10. Source: Hunter and Lafontaine [1992].
11. Source: Edge Technologies literature, Edge Technologies, Ames Iowa, USA
12. Source: Hunter and Lafontaine. [1992.

Principle of Operation

Figure 1 shows the principle of operation of an EPAM actuator. A film of an elastomeric polymer acts as an insulator or "dielectric" between two compliant electrodes. When a voltage is applied across the film, the unlike charges in each electrode attract each other, while the like charges in each electrode repel each other. The resulting forces compress the film in thickness and expand its area.

Most robotic actuators would be somewhat more complex than the basic element shown in Figure 1. Typically, several layers of polymer are stacked to produce sufficient force without the extremely high operating voltages that a single thick layer would require. Whether a single layer of polymer film or a multilayer stack is used, the basic element of Figure 1 can be incorporated into several different actuator configurations, several of which are shown in Figure 2. Note that the configurations are analogous to piezoelectric actuators. However, unlike piezoelectric devices, the stroke of EPAM actuators can be a significant fraction of their length (up to 30%). Thus, EPAM actuators can be used as linear actuators without the need for motion-amplifying transmissions. Also, unlike piezoelectric ceramics, the EPAM materials are extremely flexible and can be rolled into a cylindrical shape, as shown in Figure 2.

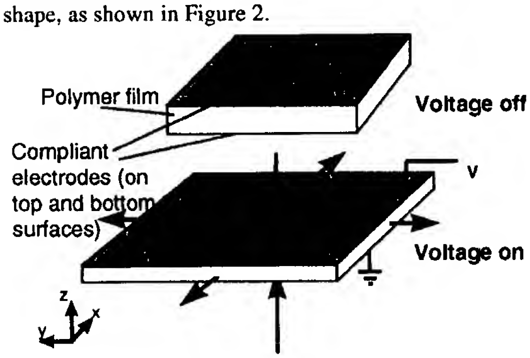


Figure 1. Principle of Operation of an EPAM Actuator

The performance and controllability of EPAM actuators can be predicted well by means of a relatively simple model. The effective compressive force per unit electrode area exerted by the electrodes on the polymer film can be calculated via the principal of virtual work. This approach assumes that the mechanical work done in deforming the dielectric to an infinitesimal degree is equal to the change in the electrical energy stored in the electric field of the device. The details of this derivation have been presented elsewhere [Pelrine, Kornbluh, and Joseph 1998]. If we assume that the electrodes are much more compliant than the polymer film itself, then this effective pressure, p, generated on the film can be expressed by

$$p = \varepsilon_r \varepsilon_o E^2 \qquad (1)$$

where ε_r is the relative dielectric constant of the polymer, ε_o is the permittivity of free space, and E is the electric field resulting from the voltage applied across the film.

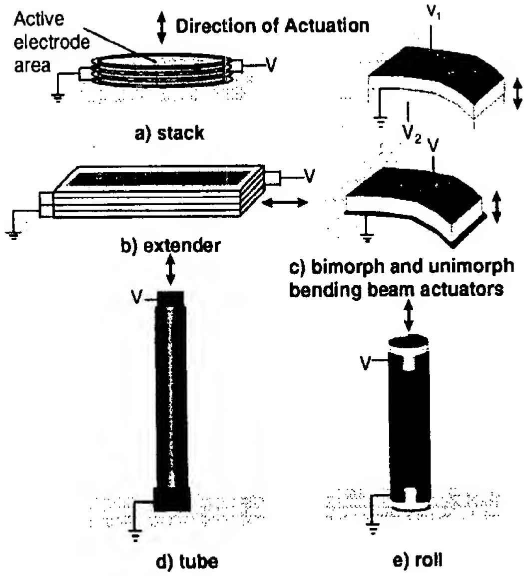


Figure 2. Possible Configurations of EPAM Actuators

Equation 1 is based on the assumption that the forces acting on the polymer film arise from the coulombic attraction of the free charges on the electrodes. Other researchers have proposed alternative mechanisms of electrostriction that generate forces in excess of those produced by coulombic attraction (e.g., Zhenyl et al. [1994]; Shkel and Klingenberg [1996]). However, these studies consider electrostriction at relatively low field levels. Our experiments have shown that at high electric fields (approaching the breakdown strength of the polymer film), coulombic forces dominate [Pelrine et al. 1997].

Equation 1 can be used to calculate the maximum force that material of a given cross-sectional area can produce with a given applied electric field. The amount of deformation of the EPAM material, which determines the stroke of the actuator, depends upon the loading on the actuator. Although the strains in the material can be quite large, we will approximate the materials as linearly elastic for purposes of illustration. In most of the actuator configurations shown in Figure 2, we can ignore mechanical constraints on the deformation of the film. In such cases, the strain in thickness of a single layer of film is

$$s_z = (-p - p_{z,load})/Y - 0.5p_{x,load}/Y - 0.5p_{y,load}/Y \qquad (2)$$

where p_{load} is the pressure on the EPAM material due to the load on the actuator, and Y is the Young's modulus of the material. We have assumed that the

polymer is incompressible and thus has a Poisson's ratio of 0.5. Similar equations can be written for the strain in the plane of the film by using a generalized Hooke's law. A different set of equations could be developed for the partially constrained deformation of the film that occurs in unimorph and bimorph configurations.

By combining Equations 1 and 2 we can calculate the electric field that must be applied across the EPAM material in order to produce a given load at a given stroke. For example, the equation that defines the performance of a rolled actuator is

$$\begin{aligned} \Delta l &= l\,(0.5p - f_{load}/wt)/Y \\ &= l\,(0.5\varepsilon_r\,\varepsilon_o\,E^2 - f_{load}/wt)/Y \end{aligned} \qquad (3)$$

where l and w are the length and width of the film, t is the film thickness, f_{load} is the axial force pushing against the actuator, and Δl is the stroke of the actuator. This force vs. stroke performance of a rolled EPAM actuator material is shown graphically in Figure 3. To avoid buckling, a rolled actuator can be used with a return spring (or be antagonistically paired with another rolled actuator). Also shown in Figure 3 are the load line for a spring or opposing EPAM actuator, and a constant load, which would be experienced, for example, when lifting a weight.

The simplest type of loading involves an unloaded and unconstrained actuator. In this case (ignoring viscoelastic losses), all of the electrical energy that is converted to mechanical work causes deformation of the material itself. It may seem at first that this loading condition is not realistic for most robotic applications because the actuator cannot produce any external force. However, the energy of deformation is elastic, so that this energy could be recovered and later used for external work when the actuation voltage is removed. This loading condition is a good benchmark for comparisons of the actuation performance of different polymer materials and comparisons of EPAM with other actuation technologies. In the simple loading case we are discussing here, the corresponding volumetric strain energy density, e, of the deformed polymer material is

$$e = ps_t/2 = [\varepsilon_r\,\varepsilon_o\,E^2]^2 / 2Y = p^2/2Y \qquad (4)$$

Equations 3 and 4 can provide us with estimates of the force, stroke, and total energy output for an EPAM actuator of any given cross-sectional area and length. Dividing the volumetric strain energy density by the density of the polymer material gives the specific energy (energy per unit mass) of the material. The specific power is simply the specific energy multiplied by the rate of actuation.

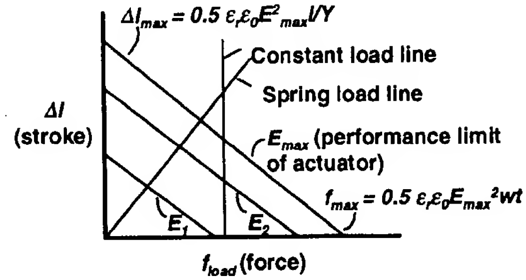


Figure 3. Rolled Actuator Force vs. Stroke

Performance and Fabrication of Electrostrictive Polymer Materials

We have identified a number of polymer materials that are capable of producing useful pressures, strains, and total energy densities. Table 2 is based on data from Pelrine, Kornbluh and Joseph [1998] and summarizes the experimentally measured maximum performance of some of these materials. As noted, the strains produced can be quite large. We have produced strains of > 30% in silicone rubber (polydimethylsiloxane) and strains of > 10% in a number of different polymers. The greatest pressure and energy density was achieved with polyurethane; however, such maximum values are not easily reproducible. Silicone rubber consistently gives a high energy density. The strains and pressures given in Table 2 should be considered the maximum values achievable under ideal conditions at the maximum sustainable electric field for each material. In practice, many factors will diminish actuator performance. These factors include viscoelastic losses in the polymer and electrodes, stiffness of the electrodes, and limitations on the applied field due to variations in the thickness or quality of the film.

The speed of response of an electrostrictive polymer actuator is limited at the most basic level only by the speed of sound across the polymer and the electrical impedance of the actuator and driving electronics [Pelrine, Kornbluh, and Joseph 1998]. We have measured pressure rise times of < 4 ms in linear actuators. We have also observed that EPAM actuators can produce sound at frequencies of at least 17 kHz; thus, the maximum speed of response may be < 1 ms. In many cases, the speed of response will be limited by the resonant modes of the actuator and driven mass. Note that in some applications, such as a rotary motor, it may be desirable to drive the actuator at resonance.

Resonant frequency can be simply calculated by using the spring rate found in Equation 3.

Table 2. Measured Electrostrictive Performance of Various Polymer Materials

Polymer (Specific type)	Energy Density (J/cm^3)	Pressure (MPa)	Strain (%)	Young's Modulus (MPa)	Electric Field (V/μm)
Polyurethane Deerfield PT6100S	0.10	1.9	11	17	160
Silicone Dow Corning Sylgard 186	0.034	0.21	32	0.7	144
Fluorosilicone Dow Corning 730	0.019	0.070	28	0.5	80
Fluoro-elastomer LaurenL143HC	0.0080	0.20	8	2.5	32
Polybutadiene Aldrich PBD	0.011	0.19	12	1.7	76
Isoprene Natural Rubber Latex	0.0052	0.094	11	0.85	67

EPAM actuator efficiency is quite high. The polymers generally have high volume resistivity, so losses during actuation are primarily due to viscoelastic damping in the polymer. These losses are generally around 5% for silicone rubber at low actuation frequencies. At a frequency of 200 Hz, these losses are approximately 20%. For many applications, efficiencies of > 80% should be feasible.

The most critical step in the fabrication of EPAM actuators is the fabrication of the polymer film. The film thickness must be uniform, in order to keep the electric field constant throughout the film and avoid areas where electrical breakdown would occur. The polymer films are typically fabricated by spin coating. Dip coating is used to produce tubular actuators. Films as thin as 2 μm have been produced although most actuators use films in the 10—100 μm range, requiring operating voltages of up to several thousand volts for maximum performance. The reduction of operating voltage by using thinner films is an area of ongoing research. Note, however, that the average electric current is extremely low (e.g., at 1 W of average power, the average current is just 0.5 mA for an operating voltage of 2,000 V). Such low current operation is inherently efficient because it results in lower losses, due to otimic heating (i^2r losses) in the wiring and electrodes.

A number of materials can be used to form the compliant electrodes. Powdered graphite that is brushed onto the film through a stencil offers sufficient conductivity but can slowly flake off the film. (Graphite was used for the measurements in Table 2.) Polymers filled with very fine conductive particles, such as carbon black, are more durable but constrain the motion with some added stiffness. These conductive polymer materials are applied by spraying or dipping.

Actuator Design and Performance

EPAM actuators can be used in robots in a variety of ways. The large stroke capability of EPAM actuators allow them to be used directly as linear actuators in much the same way as muscle is used in biological creatures. Figure 4 shows an example of this approach. Two rolled actuators are attached across the elbow joint of a 1:7 scale model of a human skeleton. While this example is intended mainly to demonstrate the similarities to biological muscle, the configuration is similar to that which might be used for applications such as moving the legs of insect-like robots or the fingers of a highly articulated hand. A typical rolled actuator for such applications has been fabricated, using silicone rubber as the electrostrictive polymer material. The actuator weighs 0.25 g (including connectors), and has an active length of 15 mm and a diameter of 2 mm. Despite its small mass and size, the actuator can produce more than 15 g of force and has a 1.5 mm stroke.

Spherical Joint Actuator

As noted above, a snake-like or serpentine manipulator poses difficult requirements for conventional actuator technologies. By analogy to snakes, worms, elephant trunks, or tentacles, muscle-like actuators are clearly appropriate for such a manipulator. A serpentine manipulator might be used to inspect and perform tasks in cluttered environments or reach inside an object for inspection. A typical serpentine manipulator consists of many links connected in series by spherical joints. The abilities of such a manipulator to reach around obstacles can be improved by maximizing the number of links, maximizing the range of motion of each link, and minimizing the length of each link, in order to increase the curvature that the manipulator can achieve. With a large number of actuators distributed along the length of the manipulator, it is important to minimize the mass of each actuator. Since it is also desirable to minimize the diameter of the manipulator, the size of the actuators is important as well. Due to their high specific energy and energy density, EPAM actuators are well suited to serpentine manipulators.

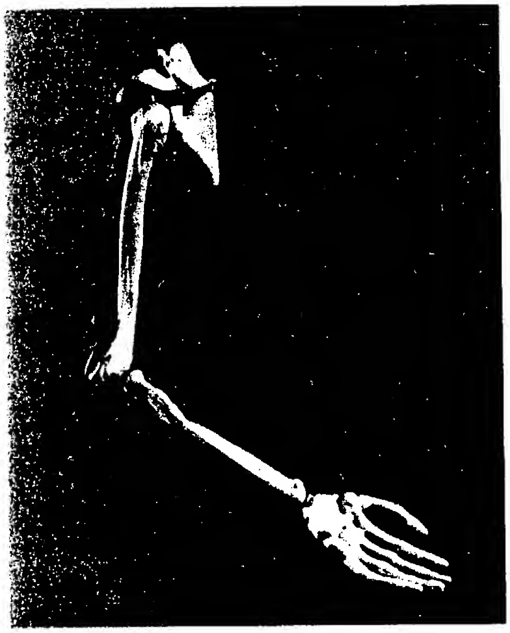


Figure 4. EPAM Roll Actuators Used as Linear Actuators on a Scale Model of a Human Arm

Figure 5 shows a spherical joint based on EPAM roll actuators. Three actuators are arranged in a triad about a central spine. The actuators are preloaded in tension. A pivot joint with a flexible shaft coupling (or a universal joint) allows the spine to bend in any direction and to resist torsion. Proportional control of the voltage to each actuator enables the pivot joint to bend in any direction. A minimum of three actuators are used to provide this motion capability, without the use of opposing springs. Thus, almost all of the mass in each link contributes to actuation. The use of three actuators also enables each link to be extended in length if the spine can telescope.

A manipulator configured as shown in Figure 5 can achieve a local radius of curvature, given by

$$R = \tfrac{1}{2}\, rl/\Delta l \qquad (5)$$

where r is the distance from the center of the spine to the attachment point of the actuator (the radius of the manipulator must be greater than r). The joint in Figure 5 is about 6 cm long and 4 cm in diameter. Figure 6 shows a kinematic model of a portion of a manipulator constructed with EPAM spherical joints. This figure illustrates the curvature that can be achieved if the stroke of each actuator is just 10% of its length. We have used a proof-of-concept joint with silicone rubber roll actuator elements to demonstrate such a stroke. The manipulator shown in Figure 6 is tapered distally because the more distal joints do not need to support the weight of the links closer to the base.

If we assume that the cross-sectional area of each actuator element is r^2, then the maximum torque that can be produced at each joint is

$$T = 2\, f_{load} r = 2pr^3 \qquad (6)$$

We can calculate the quasi-static lifting capabilities of a manipulator using EPAM technology, by applying Equation 6 and the data of Table 2 to a manipulator modeled as a straight beam supported at the base. For example, assuming that the mass of the manipulator is dominated by the mass of the actuators, a tapered manipulator 1 m long with a cross-sectional area of 25 cm^2 at the base could lift a payload of 100 g at full extension, using silicone rubber EPAM actuators. This calculation suggests that the EPAM technology is appropriate for serpentine manipulator tasks involving small reaction forces at the end effector, such as inspection.

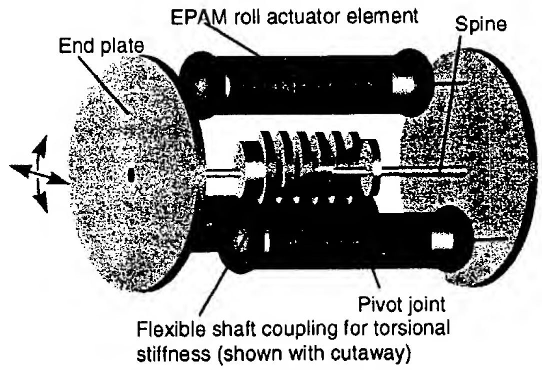


Figure 5. Spherical Joint Actuator for a Serpentine Manipulator

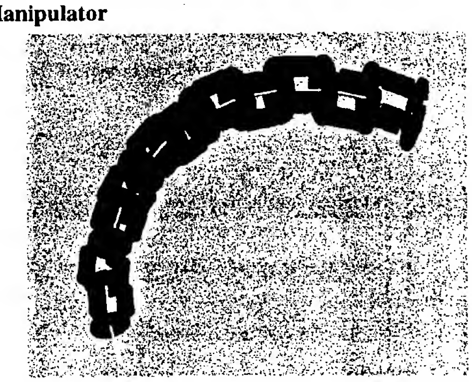


Figure 6. Kinematic Model of Serpentine Manipulator with Linked Spherical Joints

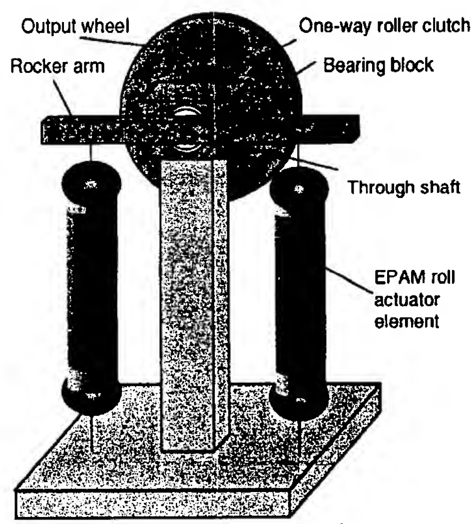
Rotary Motor

In certain applications, the deformation of the material in an EPAM actuator is not sufficient to produce the desired stroke. Other applications may require continuous rotary motion. A motor that uses repeated deformations of an EPAM actuator element can meet these requirements. The high specific energy of an EPAM actuator, combined with its rapid speed of response, suggests that the EPAM technology can produce motors with high specific power.

Figure 7 shows a simple rotary motor that converts the linear motion of an EPAM rolled actuator to rotary motion. The rolled actuator causes a rocker arm to reciprocate. The rocker arm is coupled to the output shaft through a one-way clutch that engages with the shaft in only one direction of rotation. Our proof-of-concept device uses a commercially available one-way roller clutch with a locking sprag mechanism. To enable the direction of rotation of the motor to be reversed, the clutch would have to be an active device such as an electromagnetic clutch or magnetic particle clutch; alternatively, a separate EPAM actuator element could be used to actuate a specially designed clutch. The motor requires a load on the output in excess of the frictional drag of the clutch, in order to produce motion in one direction. The output shaft can also be loaded by an inertial mass that produces motion when the motor is driven at higher frequencies. The output power is maximized by driving the motor at the frequency at which the EPAM element (coupled to the inertial mass) experiences its first longitudinal resonance.

Our proof-of-concept rotary motor was driven by a 0.25 g EPAM rolled actuator with an active length of 15 mm. The motor produced a maximum output speed of 110 rpm and a maximum torque of 1.5 mNm. The maximum output power was about 9 mW. This power was achieved by driving the EPAM element at its resonant frequency of 90 Hz. The mass of the active portion of the EPAM actuator element driving this motor was approximately 0.08 g. Therefore, the specific power of the EPAM actuator element is roughly 0.1W/g. This value compares favorably with the power achieved by most electric motors. The best rare-earth magnet electric motors can produce a specific power of about 0.5 W/g. While the best electric motors exceed the performance of our proof-of-concept device, it should be noted that our motor is a simple design that is far from optimal.

Our measurements of the EP material capabilities indicate that we can expect more than an order of magnitude improvement as more is learned about the important design parameters and configurations. To estimate the maximum achievable performance, we note that the EPAM actuator element was operated at 90 Hz. Using the full 0.034 J/g maximum specific energy measured for the silicone material in the actuator element (and ignoring the mass of the electrodes and inactive portions of the device), the specific power at 90 Hz would be over 3 W/g. A thicker roll would have a higher resonant frequency, so that the maximum theoretical specific power could be even greater. Allowing for inefficiencies in the design, the mass of the inactive portions of the device, and a safety margin below the maximum output of the material, a specific power of 1.0 W/g should be achievable.



Note: Two EPAM elements are shown. One could be replaced by a passive spring element

Figure 7. Simple Rotary Motor Based on EPAM Actuator Elements

The specific torque of the motor is 19 mNm/g, considerably greater than that of most direct-drive electromagnetic motors and rotary actuators.

Rotary motors based on piezoelectrics are increasingly used in a variety of small mechanisms. Most piezoelectric motors drive the piezoelectric elements at ultrasonic frequencies. The specific power of piezoelectric motors can exceed that of electromagnetic devices and is comparable to that projected for an EPAM motor. The specific torque of these motors is also similar to that of our EPAM motor. While the performance of piezoelectric and EPAM motors is comparable, EPAM motors have some advantages for robotic applications. Since the EPAM elements can

undergo large deformations, EPAM motors do not require the precision components that must be used in piezoelectric motors. Therefore, EPAM motors can be manufactured at lower cost from a greater variety of materials. Initial tests with rolled EPAM actuator suggest good long-term reliability and performance. Piezoelectric elements are, however, subject to fatigue failure as well as performance degradation due to aging of the material. Problems associated with cost and fatigue cracking of the piezoelectric elements have prevented the construction of large piezoelectric motors.

Summary and Conclusions

We have discussed the electrostriction of elastomeric polymers with compliant electrodes as a means of actuation. The performance of such EPAM actuators is unlike that of any other electrically powered actuator and is similar to that of biological muscle. These actuators are promising for many biologically inspired robotic and teleoperated applications. The behavior of EPAM actuators can be understood by means of a relatively simple electrostatic model in which electrostriction arises from the coulombic attraction of the free charges on the electrodes. Several materials demonstrate high energy density capabilities. Proof-of-concept devices were built to demonstrate the unique capabilities of EPAM actuators. A spherical joint actuator showed how a lightweight and compact actuator with large stroke capabilities could be used for highly articulated mechanisms. A rotary motor demonstrated that EPAM technology can produce a specific power comparable to that of electric motors. More development is needed, to improve the motor performance and design in order to develop a lightweight and low-cost motor with performance exceeding that of electromagnetic and piezoelectric motors. Such a motor would be expected to find widespread usage in robotics, teleoperation, and unmanned vehicles. Possible disadvantages of EPAM actuators include the need to operate at relatively high voltages and possible dynamic control issues for high-speed operation, due to the inherent compliance of the EPAM materials. Further research is also needed to produce larger actuators for applications requiring larger forces and motions.

Acknowledgments

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References

Aramaki, S., S. Kaneko, K. Arai, Y. Takahashi, H. Adachi, and K. Yanagisawa. 1995. "Tube Type Micro Manipulator Using Shape Memory Alloy (SMA)," *Proc. IEEE Sixth International Symposium on Micro Machine and Human Science*, Nagoya, Japan, pp. 115—120.

Baughman, R., L. Shacklette, R. Elsenbaumer, E. Pichta, and C. Becht. 1990. "Conducting Polymer Electromechanical Actuators," in *Conjugated Polymeric Materials: Opportunities in Electronics, Optoelectronics and Molecular Electronics*, eds. J.L. Bredas and R.R. Chance, Kluwer Academic Publishers, The Netherlands, pp. 559—582.

De Rossi, D., and P. Chiarelli. 1994. "Biomimetic Macromolecular Actuators," *Macro-Ion Characterization*, American Chemical Society Symposium Series Vol. 548, Ch. 40, pp. 517—530.

Hirose, S. 1993. *Biologically Inspired Robots: Snake-like Locomotors and Manipulators*, Oxford University Press, New York.

Hunter, I.W., and S. Lafontaine. 1992. "A Comparison of Muscle with Artificial Actuators," *Technical Digest of the IEEE Solid-State Sensor and Actuator Workshop*, Hilton Head, South Carolina, pp. 178—185.

Hunter, I., S. Lafontaine, J. Hollerbach, and P. Hunter. 1991. "Fast Reversible NiTi Fibers for Use in MicroRobotics," *Proc. 1991 IEEE Micro Electro Mechanical Systems—MEMS '91*, Nara, Japan, pp. 166—170.

Kornbluh, R., J. Eckerle, and G. Andeen. 1991. "Artificial Muscle: The Next Generation of Robotic Actuators," SME Paper MS91-331, presented at the Fourth World Conference of Robotics Research.

Pelrine, R., J. Eckerle, and S. Chiba. 1992. "Review of Artificial Muscle Approaches" (by invitation), in *Proc. Third International Symposium on Micro Machine and Human Science*, Nagoya, Japan.

Pelrine, R., R. Kornbluh, and J. Joseph. 1998. "Electrostriction of Polymer Dielectrics with Compliant Electrodes as a Means of Actuation," *Sensor and Actuators A: Physical 64, pp. 77—85.*

Pelrine, R, R. Kornbluh, J. Joseph, and S. Chiba. 1997. "Electrostriction of Polymer Films for Microactuators," *Proc. IEEE Tenth Annual International Workshop on Micro Electro Mechanical Systems*, Nagoya, Japan, pp. 238—243.

Shastri, S.V. 1997. "A biologically consistent model of legged locomotion gaits," *Biological Cybernetics*, Vol. 76, pp. 429—440.

Shkel, Y., and D. Klingenberg. 1996. "Material Parameters for Electrostriction," *Journal of Applied Physics*, Vol. 80(8), pp. 4566—4572.

Tobushi, H., S. Hayashi, and S. Kojima. 1992. "Mechanical Properties of Shape Memory Polymer of Polyurethane Series," *JSME International Journal*, Series I, Vol. 35, No. 3.

Zhenyl, M., J.I. Scheinbeim, J.W. Lee, and B.A. Newman. 1994. "High Field Electrostrictive Response of Polymers," *Journal of Polymer Sciences, Part B—Polymer Physics*, Vol. 32, pp. 2721—2731.